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Search for supersymmetry in pp collisions at $\sqrt{s} = 13$ tev in the single-lepton final state using the sum of masses of large-radius jets

CMS Collaboration ; Canelli, Maria Florencia ; Kilminster, Benjamin ; Aarrestad, Thea K ; Caminada, Lea ; de Cosa, Annapaoloa ; Del Burgo, Riccardo ; Donato, Silvio ; Galloni, Camilla ; Hinzmann, Andreas ; Hreus, Tomas ; Ngadiuba, Jennifer ; Pinna, Deborah ; Rauco, Giorgia ; Robmann, Peter ; Salerno, Daniel ; Schweiger, Korbinian ; Seitz, Claudia ; Takahashi, Yuta ; Zucchetta, Alberto ; et al

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Search for Supersymmetry in pp Collisions at $\sqrt{s} = 13$ TeV in the Single-Lepton Final State Using the Sum of Masses of Large-Radius Jets

A. M. Sirunyan *et al.**

(CMS Collaboration)

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Results are reported from a search for supersymmetric particles in proton-proton collisions in the final state with a single lepton, multiple jets, including at least one b -tagged jet, and large missing transverse momentum. The search uses a sample of proton-proton collision data at $\sqrt{s} = 13$ TeV recorded by the CMS experiment at the LHC, corresponding to an integrated luminosity of 35.9 fb^{-1} . The observed event yields in the signal regions are consistent with those expected from standard model backgrounds. The results are interpreted in the context of simplified models of supersymmetry involving gluino pair production, with gluino decay into either on- or off-mass-shell top squarks. Assuming that the top squarks decay into a top quark plus a stable, weakly interacting neutralino, scenarios with gluino masses up to about 1.9 TeV are excluded at 95% confidence level for neutralino masses up to about 1 TeV.

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A central goal of the physics program of the CMS experiment at the CERN LHC [1] is the search for new particles and phenomena beyond the standard model (SM), in particular, for supersymmetry (SUSY) [2–9]. During 2016, CMS recorded a data sample of proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1} , significantly extending the sensitivity to the production of new heavy particles. The search described here focuses on a generically important experimental signature that is also strongly motivated by SUSY phenomenology. This signature includes a single lepton (an electron or a muon), several jets, arising from the hadronization of energetic quarks and gluons, at least one b -tagged jet, indicative of processes involving third generation quarks, and, finally, \vec{p}_T^{miss} , the missing momentum in the direction transverse to the beam. A large value of $p_T^{\text{miss}} \equiv |\vec{p}_T^{\text{miss}}|$ can arise from the production of high momentum, weakly interacting particles that escape detection. Searches for SUSY in the single-lepton final state have been performed by both ATLAS and CMS at $\sqrt{s} = 7$ and 8 TeV [10–13] and at $\sqrt{s} = 13$ TeV [14–17]. The present analysis, which introduces extended binning and other improvements, is based largely on methodologies described in detail in Ref. [16], which include the use of large-radius jets and related kinematic variables.

In models based on SUSY, new particles are introduced such that all fermionic (bosonic) degrees of freedom in the SM are paired with corresponding bosonic (fermionic)

degrees of freedom in the extended theory. The discovery of a Higgs boson with low mass [18–23] provides a key motivation for SUSY. Stabilizing the Higgs boson mass at a low value, without invoking extreme fine-tuning of parameters, is a major theoretical challenge, referred to as the gauge hierarchy problem [24–29]. This stabilization can be achieved in so-called natural SUSY models [30–34], in which several of the SUSY partners are constrained to be light [33]: the top squarks \tilde{t}_L and \tilde{t}_R , which have the same electroweak couplings as the left- (L -) and right- (R -) handed top quarks, respectively, the bottom squark with L -handed couplings, \tilde{b}_L , the gluino \tilde{g} ; and the Higgsinos \tilde{H} . This search targets gluino pair production, which has a relatively large cross section for a given mass, with gluino decay $\tilde{g} \rightarrow t\tilde{\chi}_1^0$. This process can arise from $\tilde{g} \rightarrow \tilde{t}_1\bar{t}$, where the lighter top squark mass eigenstate \tilde{t}_1 is produced either on or off mass shell. The symbol $\tilde{\chi}_1^0$ denotes the lightest neutralino, an electrically neutral mass eigenstate that is in general a mixture of the Higgsinos and electroweak gauginos. In R -parity conserving SUSY models [35,36] in which the $\tilde{\chi}_1^0$ is the lightest supersymmetric particle, the $\tilde{\chi}_1^0$ is stable and can, in principle, account for some or all of the astrophysical dark matter [37–39]. The scenario with off-mass-shell top squarks is denoted as T1tttt [40] in simplified model scenarios [41–43]. In natural SUSY models, the top squark is typically lighter than the gluino, so we also search for scenarios with on-shell top squarks, denoted as T5tttt.

Simulated event samples for SM background processes are used to determine correction factors, typically near unity, that are used in conjunction with observed event yields in control regions to determine the SM background contribution in the signal regions. The production of $t\bar{t}$ + jets, W + jets, Z + jets, and QCD multijet events is simulated with the MC generator MADGRAPH5_AMC@NLO@NLO 2.2.2

*Full author list given at the end of the article.

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[44], with parton distribution functions taken from NNPDF 3.0 [45]. Details on the simulated SM background samples, including other processes with smaller contributions (single top quark, $t\bar{t}$ + bosons, diboson, and $t\bar{t}t\bar{t}$ production) are given in Ref. [16]. The detector simulation is performed with GEANT4 [46]. Simulated event samples for SUSY signal models, used to determine the selection efficiency for signal events, are generated with MADGRAPH5_AMC@NLO@NLO 2.2.2 with up to two additional partons at leading order accuracy and are normalized to cross sections based on Ref. [47]. Because of the large number of mass hypotheses examined in this analysis, the detector simulation in this case is performed with the CMS fast simulation package [48].

Two T1tttt benchmark models are used to illustrate typical signal behavior. The T1tttt(1800,100) model, which we refer to as a noncompressed-spectrum model (NC), has $m(\tilde{g}) = 1800$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV, and a cross section of 2.8 fb, and corresponds to a scenario with a large gluino-neutralino mass splitting. The T1tttt(1400,1000) model, with $m(\tilde{g}) = 1400$ GeV, $m(\tilde{\chi}_1^0) = 1000$ GeV, and a cross section of 25 fb, corresponds to a scenario with a small gluino-neutralino mass splitting and is referred to as a compressed-spectrum model (C).

The data were recorded with the CMS detector [49], which is constructed around a superconducting solenoid of 6 m diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are the charged particle tracking systems, composed of silicon-pixel and silicon-strip detectors, and the calorimeter systems, consisting of a lead tungstate crystal electromagnetic calorimeter and a brass and scintillator hadron calorimeter. Muons are identified and measured by gas-ionization detectors embedded in the magnetic flux-return yoke outside the solenoid. Events were selected using several triggers [50] that require either large p_T^{miss} or a single lepton (an electron or a muon), with and without significant hadronic activity. The trigger efficiency is measured in data for our analysis requirements to be nearly 100%.

Event reconstruction proceeds from particles identified by the particle-flow (PF) algorithm [51], which uses information from the tracker, calorimeters, and muon systems to identify PF candidates as electrons, muons, charged or neutral hadrons, or photons. Electrons are reconstructed by associating a charged-particle track with electromagnetic calorimeter superclusters [52]. The resulting candidate electrons are required to have transverse momentum $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.5$, and to satisfy identification criteria designed to reject light-parton jets and photon conversions. Muons are reconstructed by associating tracks in the muon system with those found in the silicon tracker [53]. Muon candidates are required to satisfy $p_T > 20$ GeV and $|\eta| < 2.4$. To select leptons from W boson decays, leptons are required to be isolated from other PF candidates. Isolation is quantified using an optimized version [16] of the mini-isolation variable originally suggested in Ref. [54], in which the

transverse energy of the particles within a cone around the lepton momentum vector is computed using a cone size that decreases as $1/p_T^\ell$, where p_T^ℓ is the transverse momentum of the lepton.

To suppress dilepton backgrounds, we veto events that contain a broader category of candidates for the second lepton, referred to as veto tracks. These include two categories of charged-particle tracks: isolated leptons satisfying looser identification criteria than lepton candidates, including a relaxed momentum requirement, $p_T > 10$ GeV, and isolated charged-hadron PF candidates, which must satisfy $p_T > 15$ GeV and $|\eta| < 2.5$. In either case, the charge of the veto track must be opposite to that of the lepton candidate in the event. To maintain a high selection efficiency for signal events, lepton veto tracks must satisfy a requirement on the quantity [55,56] $M_{T2}(\vec{p}^\ell, \vec{p}_T^v, \vec{p}_T^{\text{miss}}) < 80$ GeV and hadronic veto tracks must satisfy $M_{T2}(\vec{p}^\ell, \vec{p}_T^v, \vec{p}_T^{\text{miss}}) < 60$ GeV, where v refers to the veto track.

Charged and neutral PF candidates are clustered into jets using the anti- k_T algorithm [57] with radius parameter $R = 0.4$, as implemented in the FASTJET package [58]. Jets are required to satisfy $p_T > 30$ GeV and $|\eta| \leq 2.4$. Additional details and references are given in Ref. [16] on the p_T - and η -dependent jet energy calibration [59], the jet identification requirements, and the subtraction of the energy contribution to the jet p_i from multiple proton-proton interactions from the same or neighboring beam crossings (pileup) [60]. A subset of the jets are tagged as originating from b quarks using the combined secondary vertex algorithm [61,62].

We further cluster the jets with $R = 0.4$ (small- R jets), including those associated with isolated leptons, into $R = 1.4$ (large- R) jets using the anti- k_T algorithm. The masses $m(J_i)$ of the large- R jets reflect the p_T spectrum and multiplicity of the clustered objects, as well as their angular spread. The variable M_J is defined as the sum of all large- R jet masses: $M_J = \sum_{J_i=\text{large-}R\text{ jets}} m(J_i)$. For $t\bar{t}$ events with a small contribution from initial-state radiation (ISR), the M_J distribution has an approximate cutoff at $2m_t$. In contrast, the M_J distribution for signal events extends to larger values because of the presence of multiple top quarks in the decay chain. The presence of a significant amount of ISR generates a high- M_J tail in the $t\bar{t}$ background, producing the main source of background in the analysis.

The missing transverse momentum \vec{p}_T^{miss} is defined as the negative vector sum of the transverse momenta of all PF candidates. To separate backgrounds characterized by the presence of a single W boson decaying leptonically, but without any other source of p_T^{miss} , we use the transverse mass $m_T = \sqrt{2p_T^\ell p_T^{\text{miss}} [1 - \cos(\Delta\phi_{\ell, \vec{p}_T^{\text{miss}}})]}$, where $\Delta\phi_{\ell, \vec{p}_T^{\text{miss}}}$ is the difference between the azimuthal angles of p_T^ℓ and \vec{p}_T^{miss} . The quantity H_T is defined as the scalar sum of the transverse momenta of all the small- R jets passing the selection, while $S_T = H_T + p_T^\ell$.

We select events with exactly one isolated charged lepton (an electron or a muon), no veto tracks, $S_T > 500$ GeV, $p_T^{\text{miss}} > 200$ GeV, and at least six small- R jets, at least one of which is b tagged. After this set of requirements, referred to as the baseline selection, about 80% of the SM background arises from $t\bar{t}$ production. The contributions from events with a single top quark or a W boson in association with jets are each about 6%–8%; much of the remainder arises from events with a $t\bar{t}$ pair produced in association with a vector boson. After applying the baseline selection, the background from QCD multijet events is negligible.

The analysis is performed using four regions in the M_J - m_T plane: three control regions (CR) and one signal region:

- (i) R1 (CR): $m_T \leq 140$ GeV, $250 \leq M_J \leq 400$ GeV.
- (ii) R2 (CR): $m_T \leq 140$ GeV, $M_J > 400$ GeV.
- (iii) R3 (CR): $m_T > 140$ GeV, $250 \leq M_J \leq 400$ GeV.
- (iv) R4 (signal region): $m_T > 140$ GeV, $M_J > 400$ GeV.

All four regions are divided in bins of p_T^{miss} , forming three largely independent M_J - m_T planes:

- (i) Three p_T^{miss} bins: $200 < p_T^{\text{miss}} \leq 350$ GeV, $350 < p_T^{\text{miss}} \leq 500$ GeV, $p_T^{\text{miss}} > 500$ GeV.

Regions R2 and R4, which have high M_J , are further divided into bins according to the number of small- R jets (N_{jets}) and the number of b -tagged jets (N_b) as follows:

- (ii) Two N_{jets} bins: $6 \leq N_{\text{jets}} \leq 8$, $N_{\text{jets}} \geq 9$.
- (iii) Three N_b bins: $N_b = 1$, $N_b = 2$, $N_b \geq 3$, giving a total of 18 bins each. Backgrounds with a single W boson decaying leptonically are strongly suppressed by the requirement $m_T > 140$ GeV, so the background in R3 and R4 is dominated by dilepton $t\bar{t}$ events. Approximately half of the dilepton background events in R4 contain a missed electron or muon, and the other half contain a hadronically decaying τ lepton. Given that the main background processes have two or fewer b quarks, the total SM contribution to the $N_b \geq 3$ bins is very small and is driven by the b tag misidentification rate. Signal events in the T1tttt and T5tttt models populate primarily the bins with $N_b \geq 2$.

The method for predicting the background yields takes advantage of the near absence of correlation between the M_J and m_T variables in R1–R4, which is a consequence of the high jet multiplicity, p_T^{miss} , and S_T requirements applied in the baseline selection [16]. To satisfy these requirements, background events must typically contain additional jets from ISR. Even though the background at low m_T arises largely from single-lepton $t\bar{t}$ events, while the background at high m_T is dominated by dilepton $t\bar{t}$ events, the shapes of the M_J distributions at low and high m_T become very similar in the presence of multiple ISR jets. We therefore measure this shape at low m_T (R1, R2) and extrapolate it to high m_T to obtain the background prediction in R4. The fitted mean background yields in R1–R4 are thus related by the constraint $\mu_{R4}^{\text{bkg}} = \kappa \mu_{R3}^{\text{bkg}} \mu_{R2}^{\text{bkg}} / \mu_{R1}^{\text{bkg}}$. Here, κ is a near-unity

correction factor obtained from MC simulation of the total background that accounts for a residual m_T - M_J correlation:

$$\kappa = \frac{\mu_{R4}^{\text{MC bkg}} / \mu_{R2}^{\text{MC bkg}}}{\mu_{R3}^{\text{MC bkg}} / \mu_{R1}^{\text{MC bkg}}} \quad (1)$$

This constraint is imposed by relating the expected yields in R1–R4 to three parameters: an overall background normalization λ and two ratios $R(m_T)$ and $R(M_J)$, where the expected background yields are given by $\mu_{R1}^{\text{bkg}} = \lambda$, $\mu_{R2}^{\text{bkg}} = \lambda R(M_J)$, $\mu_{R3}^{\text{bkg}} = \lambda R(m_T)$, and $\mu_{R4}^{\text{bkg}} = \kappa \lambda R(M_J) R(m_T)$. These quantities are defined such that there is one value of $R(M_J)$ and κ for each bin of p_T^{miss} , N_{jets} , and N_b . Because regions R1 and R3 are integrated in N_{jets} and N_b , the fit parameters λ and $R(m_T)$ are defined such that there is only one value of these quantities for each bin in p_T^{miss} .

We perform two types of maximum likelihood fits, which are described in detail in Ref. [16]. The predictive fit uses the observed yields in R1–R3, assuming no signal contribution, to propagate the uncertainties to λ , $R(M_J)$, and $R(m_T)$. The global fit uses the observed yields in all four regions R1–R4 and allows a signal contribution with a single normalization parameter. The global fit accounts for signal contamination in R1–R3, which is typically less than 10%, and is used to compute signal limits and significances. The results from the predictive fit simplify theoretical reinterpretation in terms of other models by only requiring comparison of observed and predicted yields in R4 rather than all four regions. In both cases, the likelihood function is written as a product of Poisson distributions for the relevant contributions in bins of p_T^{miss} , N_{jets} , and N_b within R2 and R4, taking into account the correlated yields between the unbinned regions R1 and R3.

Systematic uncertainties in the background prediction are incorporated in the uncertainty in the double ratio correction factor κ . Discrepancies between the value of κ predicted by simulation and the true value of κ in the data can in principle arise from mismodeling of the background composition or its properties, including detector effects.

To assess the potential impact of such effects on κ , two control samples in data are used: a five-jet control sample and a dilepton control sample. The five-jet control sample is completely dominated by background processes and has a SM composition very similar to that of the analysis regions. In particular, this sample probes the rate at which p_T^{miss} is mismeasured in single-lepton events, which could increase the tail of the m_T distribution. Such events account for about 7% of the background in the signal region at high p_T^{miss} . This small event category can have a κ value that departs significantly from unity, and it is important to validate the modeling of such effects. Using the analogous R1–R4 regions in the $N_{\text{jets}} = 5$ control sample, κ values are measured in data and are found to be consistent with those obtained from simulation. Because of this consistency, the

statistical uncertainty obtained from the comparison in the $N_{\text{jets}} = 5$ control sample is assigned as an uncertainty in κ for each p_T^{miss} bin. These uncertainties are taken to be fully correlated over the N_{jets} and N_b bins.

The dilepton control sample is used to test the degree of similarity between the M_J shapes of single-lepton and dilepton $t\bar{t}$ events in the presence of ISR. This sample includes not only events with two identified isolated leptons, but also events with one lepton and an oppositely charged veto track. The usual R3 and R4 regions are replaced by dilepton events, and the quantity κ is measured in bins of N_{jets} . As in the five-jet control sample, the values of κ measured in data are found to be consistent with those observed in simulation, and uncertainties are assigned in a similar way. The uncertainties are treated as independent across N_{jets} bins but fully correlated across N_b and p_T^{miss} bins. The uncertainties from the dilepton and five-jet control samples are treated as uncorrelated. Studies of a broad range of potential mismodeling effects in simulation show that all such effects would be evident in these control samples.

Systematic uncertainties in the expected signal yields account for uncertainties in the trigger, lepton identification, jet identification, and b tagging efficiencies in simulated data, uncertainties in the distributions of p_T^{miss} , the number of pileup vertices, and ISR jet multiplicity, and uncertainties in the jet energy corrections, QCD scales, and integrated luminosity [63]. The combined effect of all signal-related uncertainties is typically about 25%.

Table I lists the observed event yields in region R4 in data, together with the mean background yields from the predictive fit and the expected signal yields from two benchmark model points. The uncertainties in the predicted background yields include the statistical uncertainties on the event yields in R1–R4 in data, the statistical uncertainties in the κ values arising from the finite size of simulated event samples, and the systematic uncertainties in κ as assessed from the data control samples. The observed yields are consistent with the background predictions in all of the 18 signal bins within 2 standard deviations, with most of the 18 bins consistent within 1 s.d. The R4 bins with $p_T^{\text{miss}} > 500$ GeV show an underprediction of the background with respect to the observed yields. However, accounting for the correlations arising from the use of a single, integrated yield in R3 across bins in N_{jets} and N_b , the significance of the discrepancy in these six bins in R4 is only 1.9 s.d., mostly due to the bins with $N_b = 1$.

To simplify the reinterpretation of the results in terms of other theoretical models, we provide predicted mean background yields for four aggregated search bins, shown in Table II. The aggregate bins are defined such that at least one bin will provide sensitivity to most of the models for which the finely binned analysis has sensitivity. Since the aggregate bins overlap, they are intended to be used one at a time, unlike the 18 nonoverlapping signal bins, which are considered simultaneously in the fit. Each prediction

TABLE I. Observed event yields and mean background yields from the predictive fit in the 18 bins of the signal region R4. Each bin is specified by the values of p_T^{miss} , N_{jets} , and N_b . The uncertainties in κ include both a statistical component from the size of the MC samples and a systematic component assessed from the data control samples. The uncertainty in the predicted event yield includes both of these and the statistical uncertainties associated with the data control regions. Yields for the two T1tttt benchmark models NC and C are also given.

N_{jets}	N_b	NC	C	κ	Predicted	Observed
$200 < p_T^{\text{miss}} \leq 350$ GeV						
6–8	1	0.4	1.9	1.2 ± 0.2	85 ± 14	106
6–8	2	0.6	3.0	1.2 ± 0.2	55.1 ± 9.3	75
6–8	≥ 3	0.6	2.2	1.5 ± 0.2	16.4 ± 3.0	16
≥ 9	1	0.2	1.6	1.0 ± 0.2	6.5 ± 1.5	11
≥ 9	2	0.3	2.1	1.2 ± 0.3	7.6 ± 1.9	11
≥ 9	≥ 3	0.4	3.1	1.4 ± 0.3	2.3 ± 0.7	2
$350 < p_T^{\text{miss}} \leq 500$ GeV						
6–8	1	0.7	1.1	1.0 ± 0.3	17.4 ± 6.6	25
6–8	2	0.9	1.3	1.1 ± 0.4	13.7 ± 5.3	10
6–8	≥ 3	0.8	0.9	1.3 ± 0.4	3.8 ± 1.6	1
≥ 9	1	0.3	1.0	1.1 ± 0.4	1.3 ± 0.6	2
≥ 9	2	0.5	1.1	0.8 ± 0.3	1.6 ± 0.8	2
≥ 9	≥ 3	0.7	2.1	1.2 ± 0.5	0.6 ± 0.4	0
$p_T^{\text{miss}} > 500$ GeV						
6–8	1	2.5	0.6	1.0 ± 0.3	1.9 ± 1.5	8
6–8	2	3.6	1.0	1.0 ± 0.4	0.9 ± 0.7	4
6–8	≥ 3	3.2	0.4	1.5 ± 0.6	0.4 ± 0.4	1
≥ 9	1	1.0	0.7	1.0 ± 0.4	0.2 ± 0.2	2
≥ 9	2	1.8	1.2	1.0 ± 0.4	0.1 ± 0.1	0
≥ 9	≥ 3	2.3	1.7	3.1 ± 1.5	0.1 ± 0.1	0

includes all sources of uncertainty. The choice of the best aggregate bin will depend on the model under study. For the T1tttt benchmark models considered in this Letter, using the aggregate bins results in expected upper limits on the

TABLE II. Observed event yields and mean background yields from the predictive fit in four aggregate search bins. In all four cases, the predicted yields refer to the signal region R4 with the standard $m_{T>140}$ GeV and $M_J > 400$ GeV requirements applied in addition to the baseline selection. Unlike the finely binned approach, where all 18 background predictions are computed simultaneously, the four aggregate bin predictions are computed separately. The aggregate bins overlap, causing their background predictions to be highly correlated. Yields for the two T1tttt benchmark models NC and C are also given.

p_T^{miss} [GeV]	N_{jets}	N_b	NC	C	κ	Predicted	Observed
>200	≥ 9	≥ 3	3.4	6.9	1.4 ± 0.3	3.1 ± 0.8	2
>350	≥ 9	≥ 2	5.3	6.2	1.0 ± 0.4	2.7 ± 1.2	2
>500	≥ 6	≥ 3	5.4	2.1	1.7 ± 0.6	0.5 ± 0.4	1
>500	≥ 9	≥ 1	5.1	3.6	1.2 ± 0.4	0.4 ± 0.4	2

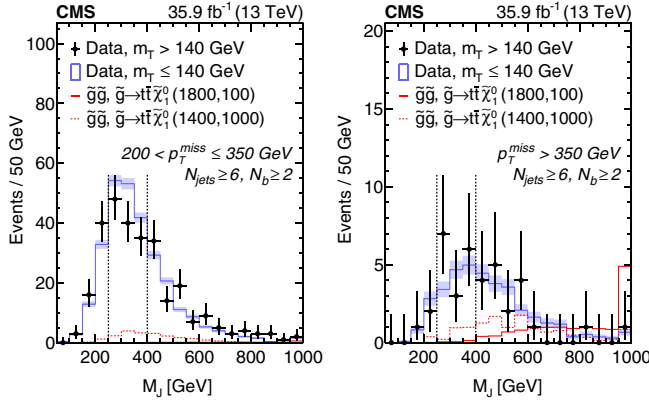


FIG. 1. Distributions of M_J observed in data for $200 < p_T^{\text{miss}} \leq 350$ GeV (left) and $p_T^{\text{miss}} > 350$ GeV (right) with the baseline selection and either $m_T \leq 140$ GeV or $m_T > 140$ GeV. In each plot, the data at low m_T have been normalized to the yield observed at high m_T . The vertical dashed lines at $M_J = 250$ and 400 GeV show the boundaries separating the control and signal regions. The data are integrated over $N_{\text{jets}} \geq 6$ and $N_b \geq 2$. Two SUSY benchmark models, whose contributions are small in the lower p_T^{miss} region, are shown in the solid and dashed red histograms. Overflow events are included in the uppermost bins.

cross sections that are 20%–50% higher than those resulting from the full analysis.

Figure 1 compares the shapes of the M_J distributions observed in data in the single-lepton sample for $m_T \leq 140$ GeV and $m_T > 140$ GeV in two regions of p_T^{miss} . The shapes of the two M_J distributions for each p_T^{miss} region are very similar, as expected in the absence of signal. A further correction is applied via the κ factors listed in Table I in M_J ranges larger than the binning shown in the figure. The lower- p_T^{miss} region shows the background behavior with higher statistics, while the higher- p_T^{miss} region has higher sensitivity to the signal.

Figure 2 shows an interpretation of the results as exclusion limits at 95% C.L. for T1tttt and T5tttt. The limits are obtained using the CL_s method with a profile-likelihood ratio as the test statistic, using asymptotic approximations for the distribution of the test statistic [64–66]. The color map shows the cross section upper limits as a function of $m(\tilde{g})$ and $m(\tilde{\chi}_1^0)$ for T1tttt, assuming a 100% branching fraction for the decay $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$. The T1tttt model points below the dark solid curve, which extend up to gluino masses of about 1.9 TeV for neutralino masses up to 1 TeV, have a theoretical cross section above the observed cross section upper limit and are thus excluded by this analysis. The dotted black lines around the observed mass limits show the impact of the theoretical uncertainties in the overall signal cross sections arising from uncertainties in the parton distribution functions and the renormalization and factorization scales.

Model points below the light solid curve are excluded at 95% C.L. for the T5tttt model, where it is assumed that the

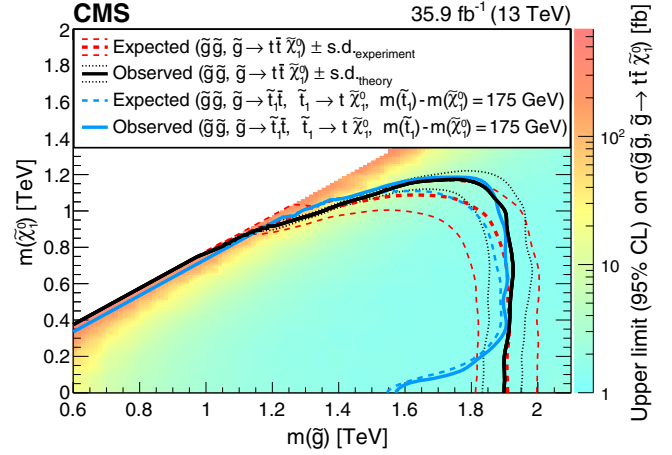


FIG. 2. Observed and expected excluded gluino and neutralino masses at 95% C.L. for the T1tttt and T5tttt models. The black (red) lines show the observed (expected) exclusion and the range associated with the theoretical (experimental) uncertainties for the T1tttt model. The solid (dashed) blue line shows the observed (expected) exclusion for the T5tttt model. The uncertainties for the T5tttt exclusion limits are not shown and are similar to those for the T1tttt model. The color map shows the observed cross section upper limits for the T1tttt model.

top squark mass is 175 GeV above the neutralino mass, a limiting case in terms of sensitivity to the decay kinematics. The T5tttt simulation does not explicitly include direct top squark pair production. Studies presented in Ref. [16] demonstrate that the effect of this contribution is very small for most of the space of T5tttt model points considered here. For most of the excluded region, the boundaries for T1tttt and T5tttt are very similar, indicating only a weak overall sensitivity to the value of the top squark mass. At low values of $m(\tilde{\chi}_1^0)$ in T5tttt, the sensitivity is reduced because the neutralino carries very little momentum; however, some sensitivity is still provided by dilepton events that escape the lepton veto [16]. For both the T1tttt and T5tttt models, expected limits are computed using the background-only hypothesis, with nuisance parameters assuming their best fit values from the observed data. All limits are computed using results from the global fit.

In summary, we have performed a search for an excess event yield above that expected for SM processes using a data sample of proton-proton collision events with an integrated luminosity of 35.9 fb^{-1} at $\sqrt{s} = 13$ TeV. The signature is characterized by large missing transverse momentum, a single isolated lepton, multiple jets, and at least one b -tagged jet. No significant excesses above the SM backgrounds are observed. The results are interpreted in the framework of simplified models that describe natural SUSY scenarios. For gluino pair production followed by the three-body decay $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ (T1tttt model), gluinos with masses below 1.9 TeV are excluded at 95% confidence level for neutralino masses up to about 1 TeV. For the two-body

gluino decay $\tilde{g} \rightarrow \tilde{t}_1 \bar{t}$ with $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ (T5tttt model), the results are generally similar, except at low neutralino masses, where the excluded gluino mass is somewhat lower. These results extend previous gluino mass limits by about 300 GeV and are among the most stringent constraints on these simplified models of SUSY to date.

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Gascon,³⁴ M. Gouzevitch,³⁴ G. Grenier,³⁴ B. Ille,³⁴

- F. Lagarde,³⁴ I. B. Laktineh,³⁴ M. Lethuillier,³⁴ L. Mirabito,³⁴ A. L. Pequegnot,³⁴ S. Perries,³⁴ A. Popov,^{34,1} V. Sordini,³⁴ M. Vander Donckt,³⁴ S. Viret,³⁴ A. Khvedelidze,^{35,g} Z. Tsamalaidze,^{36,g} C. Autermann,³⁷ S. Beranek,³⁷ L. Feld,³⁷ M. K. Kiesel,³⁷ K. Klein,³⁷ M. Lipinski,³⁷ M. Preuten,³⁷ C. Schomakers,³⁷ J. Schulz,³⁷ T. Verlage,³⁷ A. Albert,³⁸ M. Brodski,³⁸ E. Dietz-Laursonn,³⁸ D. Duchardt,³⁸ M. Endres,³⁸ M. Erdmann,³⁸ S. Erdweg,³⁸ T. Esch,³⁸ R. Fischer,³⁸ A. Güth,³⁸ M. Hamer,³⁸ T. Hebbeker,³⁸ C. Heidemann,³⁸ K. Hoepfner,³⁸ S. Knutzen,³⁸ M. Merschmeyer,³⁸ A. Meyer,³⁸ P. Millet,³⁸ S. Mukherjee,³⁸ M. Olschewski,³⁸ K. Padeken,³⁸ T. Pook,³⁸ M. Radziej,³⁸ H. Reithler,³⁸ M. Rieger,³⁸ F. Scheuch,³⁸ D. Teyssier,³⁸ S. Thüer,³⁸ G. Flügge,³⁹ B. Kargoll,³⁹ T. Kress,³⁹ A. Künsken,³⁹ J. Lingemann,³⁹ T. Müller,³⁹ A. Nehr Korn,³⁹ A. Nowack,³⁹ C. Pistone,³⁹ O. Pooth,³⁹ A. Stahl,^{39,m} M. Aldaya Martin,⁴⁰ T. Arndt,⁴⁰ C. Asawatangtrakuldee,⁴⁰ K. Beernaert,⁴⁰ O. Behnke,⁴⁰ U. 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Hinzmann,⁴¹ M. Hoffmann,⁴¹ A. Junkes,⁴¹ A. Karavdina,⁴¹ R. Klanner,⁴¹ R. Kogler,⁴¹ N. Kovalchuk,⁴¹ S. Kurz,⁴¹ T. Lapsien,⁴¹ I. Marchesini,⁴¹ D. Marconi,⁴¹ M. Meyer,⁴¹ M. Niedziela,⁴¹ D. Nowatschin,⁴¹ F. Pantaleo,^{41,m} T. Peiffer,⁴¹ A. Perieanu,⁴¹ C. Scharf,⁴¹ P. Schleper,⁴¹ A. Schmidt,⁴¹ S. Schumann,⁴¹ J. Schwandt,⁴¹ J. Sonneveld,⁴¹ H. Stadie,⁴¹ G. Steinbrück,⁴¹ F. M. Stober,⁴¹ M. Stöver,⁴¹ H. Tholen,⁴¹ D. Troendle,⁴¹ E. Usai,⁴¹ L. Vanelderen,⁴¹ A. Vanhoefer,⁴¹ B. Vormwald,⁴¹ M. Akbiyik,⁴² C. Barth,⁴² S. Baur,⁴² E. Butz,⁴² R. Caspart,⁴² T. Chwalek,⁴² F. Colombo,⁴² W. De Boer,⁴² A. Dierlamm,⁴² B. Freund,⁴² R. Friese,⁴² M. Giffels,⁴² A. Gilbert,⁴² D. Haitz,⁴² F. Hartmann,^{42,m} S. M. Heindl,⁴² U. Husemann,⁴² F. Kassel,^{42,m} S. Kudella,⁴² H. Mildner,⁴² M. U. Mozer,⁴² Th. Müller,⁴² M. Plagge,⁴² G. Quast,⁴² K. Rabbertz,⁴² M. Schröder,⁴² I. Shvetsov,⁴² G. Sieber,⁴² H. J. Simonis,⁴² R. Ulrich,⁴² S. Wayand,⁴² M. Weber,⁴² T. Weiler,⁴² S. Williamson,⁴² C. Wöhrmann,⁴² R. Wolf,⁴² G. Anagnostou,⁴³ G. Daskalakis,⁴³ T. Geralis,⁴³ V. A. Giakoumopoulou,⁴³ A. Kyriakis,⁴³ D. Loukas,⁴³ I. Topsis-Giotis,⁴³ S. Kesisoglou,⁴⁴ A. Panagiotou,⁴⁴ N. Saoulidou,⁴⁴ I. Evangelou,⁴⁵ C. Foudas,⁴⁵ P. Kokkas,⁴⁵ N. Manthos,⁴⁵ I. Papadopoulos,⁴⁵ E. Paradas,⁴⁵ J. Strogas,⁴⁵ F. A. Triantis,⁴⁵ M. Csanad,⁴⁶ N. Filipovic,⁴⁶ G. Pasztor,⁴⁶ G. Bencze,⁴⁷ C. Hajdu,⁴⁷ D. Horvath,^{47,q} Á. Hunyadi,⁴⁷ F. Sikler,⁴⁷ V. Veszpremi,⁴⁷ G. Vesztergombi,^{47,r} A. J. Zsigmond,⁴⁷ N. Beni,⁴⁸ S. Czellar,⁴⁸ J. Karancsi,^{48,s} A. Makovec,⁴⁸ J. Molnar,⁴⁸ Z. Szillasi,⁴⁸ M. Bartók,^{49,r} P. Raics,⁴⁹ Z. L. Trocsanyi,⁴⁹ B. Ujvari,⁴⁹ S. Choudhury,⁵⁰ J. R. Komaragiri,⁵⁰ S. Bahinipati,^{51,t} S. Bhowmik,⁵¹ P. Mal,⁵¹ K. Mandal,⁵¹ A. Nayak,^{51,u} D. K. Sahoo,^{51,t} N. Sahoo,⁵¹ S. K. Swain,⁵¹ S. Bansal,⁵² S. B. Beri,⁵² V. Bhatnagar,⁵² U. Bhawandeep,⁵² R. Chawla,⁵² N. Dhingra,⁵² A. K. Kalsi,⁵² A. Kaur,⁵² M. Kaur,⁵² R. Kumar,⁵² P. Kumari,⁵² A. Mehta,⁵² J. B. Singh,⁵² G. Walia,⁵² Ashok Kumar,⁵³ Aashaq Shah,⁵³ A. Bhardwaj,⁵³ S. Chauhan,⁵³ B. C. Choudhary,⁵³ R. B. Garg,⁵³ S. Keshri,⁵³ A. Kumar,⁵³ S. Malhotra,⁵³ M. Naimuddin,⁵³ K. Ranjan,⁵³ R. Sharma,⁵³ V. Sharma,⁵³ R. Bhardwaj,⁵⁴ R. Bhattacharya,⁵⁴ S. Bhattacharya,⁵⁴ S. Dey,⁵⁴ S. Dutt,⁵⁴ S. Dutta,⁵⁴ S. Ghosh,⁵⁴ N. Majumdar,⁵⁴ A. Modak,⁵⁴ K. Mondal,⁵⁴ S. Mukhopadhyay,⁵⁴ S. Nandan,⁵⁴ A. Purohit,⁵⁴ A. Roy,⁵⁴ D. Roy,⁵⁴ S. Roy Chowdhury,⁵⁴ S. Sarkar,⁵⁴ M. Sharan,⁵⁴ S. Thakur,⁵⁴ P. K. Behera,⁵⁵ R. Chudasama,⁵⁶ D. Dutta,⁵⁶ V. Jha,⁵⁶ V. Kumar,⁵⁶ A. K. Mohanty,^{56,m} P. K. Netrakanti,⁵⁶ L. M. Pant,⁵⁶ P. Shukla,⁵⁶ A. Topkar,⁵⁶ T. Aziz,⁵⁷ S. Dugad,⁵⁷ B. Mahakud,⁵⁷ S. Mitra,⁵⁷ G. B. Mohanty,⁵⁷ B. Parida,⁵⁷ N. Sur,⁵⁷ B. Sutar,⁵⁷ S. Banerjee,⁵⁸ S. Bhattacharya,⁵⁸ S. Chatterjee,⁵⁸ P. Das,⁵⁸ M. Guchait,⁵⁸ Sa. Jain,⁵⁸ S. Kumar,⁵⁸ M. Maity,^{58,v} G. Majumder,⁵⁸ K. Mazumdar,⁵⁸ T. Sarkar,^{58,v} N. Wickramage,^{58,w} S. Chauhan,⁵⁹ S. Dube,⁵⁹ V. Hegde,⁵⁹ A. Kapoor,⁵⁹ K. Kothekar,⁵⁹ S. Pandey,⁵⁹ A. Rane,⁵⁹ S. Sharma,⁵⁹ S. Chenarani,^{60,x} E. Eskandari Tadavani,⁶⁰ S. M. Etesami,^{60,x} M. Khakzad,⁶⁰ M. Mohammadi Najafabadi,⁶⁰ M. Naseri,⁶⁰ S. Pakinat Mehdiabadi,^{60,y} F. Rezaei Hosseinabadi,⁶⁰ B. Safarzadeh,^{60,z} M. Zeinali,⁶⁰ M. Felcini,⁶¹ M. Grunewald,⁶¹ M. Abbrescia,^{62a,62b} C. Calabria,^{62a,62b} C. Caputo,^{62a,62b} A. Colaleo,^{62a} D. Creanza,^{62a,62c} L. Cristella,^{62a,62b} N. De Filippis,^{62a,62c} M. De Palma,^{62a,62b} F. Errico,^{62a,62b} L. Fiore,^{62a} G. Iaselli,^{62a,62c} S. Lezki,^{62a,62b} G. Maggi,^{62a,62c} M. Maggi,^{62a} G. Miniello,^{62a,62b} S. My,^{62a,62b} S. Nuzzo,^{62a,62b} A. Pompili,^{62a,62b} G. Pugliese,^{62a,62c} R. Radogna,^{62a,62b} A. Ranieri,^{62a} G. Selvaggi,^{62a,62b} A. Sharma,^{62a} L. Silvestris,^{62a,m} R. Venditti,^{62a} P. Verwilligen,^{62a} G. Abbiendi,^{63a} C. Battilana,^{63a} D. Bonacorsi,^{63a,63b} S. Braibant-Giacomelli,^{63a,63b} L. Brigliadori,^{63a,63b} R. Campanini,^{63a,63b} P. Capiluppi,^{63a,63b}

A. Castro,^{63a,63b} F. R. Cavallo,^{63a} S. S. Chhibra,^{63a,63b} G. Codispoti,^{63a,63b} M. Cuffiani,^{63a,63b} G. M. Dallavalle,^{63a} F. Fabbri,^{63a}
A. Fanfani,^{63a,63b} D. Fasanella,^{63a,63b} P. Giacomelli,^{63a} L. Guiducci,^{63a,63b} S. Marcellini,^{63a} G. Masetti,^{63a} F. L. Navarria,^{63a,63b}
A. Perrotta,^{63a} A. M. Rossi,^{63a,63b} T. Rovelli,^{63a,63b} G. P. Siroli,^{63a,63b} N. Tosi,^{63a,63b,m} S. Albergo,^{64a,64b} S. Costa,^{64a,64b}
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V. Ciulli,^{65a,65b} C. Civinini,^{65a} R. D'Alessandro,^{65a,65b} E. Focardi,^{65a,65b} P. Lenzi,^{65a,65b} M. Meschini,^{65a} S. Paoletti,^{65a}
L. Russo,^{65a,aa} G. Sguazzoni,^{65a} D. Strom,^{65a} L. Viliani,^{65a,65b,m} L. Benussi,⁶⁶ S. Bianco,⁶⁶ F. Fabbri,⁶⁶ D. Piccolo,⁶⁶
F. Primavera,^{66,m} V. Calvelli,^{67a,67b} F. Ferro,^{67a} E. Robutti,^{67a} S. Tosi,^{67a,67b} L. Brianza,^{68a,68b} F. Brivio,^{68a,68b} V. Ciriolo,^{68a,68b}
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A. Boletti,^{70a,70b} R. Carlin,^{70a,70b} A. Carvalho Antunes De Oliveira,^{70a,70b} P. Checchia,^{70a} P. De Castro Manzano,^{70a}
T. Dorigo,^{70a} U. Dosselli,^{70a} F. Gasparini,^{70a,70b} U. Gasparini,^{70a,70b} A. Gozzelino,^{70a} S. Lacaprara,^{70a} M. Margoni,^{70a,70b}
A. T. Meneguzzo,^{70a,70b} N. Pozzobon,^{70a,70b} P. Ronchese,^{70a,70b} R. Rossin,^{70a,70b} F. Simonetto,^{70a,70b} E. Torassa,^{70a}
M. Zanetti,^{70a,70b} P. Zotto,^{70a,70b} G. Zumerle,^{70a,70b} A. Braghieri,^{71a} F. Fallavollita,^{71a,71b} A. Magnani,^{71a,71b} P. Montagna,^{71a,71b}
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A. Santocchia,^{72a,72b} D. Spiga,^{72a} K. Androsov,^{73a} P. Azzurri,^{73a,m} G. Bagliesi,^{73a} J. Bernardini,^{73a} T. Boccali,^{73a}
L. Borrello,^{73a} R. Castaldi,^{73a} M. A. Ciocci,^{73a,73b} R. Dell'Orso,^{73a} G. Fedi,^{73a} L. Giannini,^{73a,73c} A. Giassi,^{73a}
M. T. Grippo,^{73a,aa} F. Ligabue,^{73a,73c} T. Lomtadze,^{73a} E. Manca,^{73a,73c} G. Mandorli,^{73a,73c} L. Martini,^{73a,73b} A. Messineo,^{73a,73b}
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M. Costa,^{75a,75b} R. Covarelli,^{75a,75b} A. Degano,^{75a,75b} N. Demaria,^{75a} B. Kiani,^{75a,75b} C. Mariotti,^{75a} S. Maselli,^{75a}
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G. Della Ricca,^{76a,76b} A. Zanetti,^{76a} D. H. Kim,⁷⁷ G. N. Kim,⁷⁷ M. S. Kim,⁷⁷ J. Lee,⁷⁷ S. Lee,⁷⁷ S. W. Lee,⁷⁷ Y. D. Oh,⁷⁷
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T. J. Kim,⁸⁰ S. Cho,⁸¹ S. Choi,⁸¹ Y. Go,⁸¹ D. Gyun,⁸¹ S. Ha,⁸¹ B. Hong,⁸¹ Y. Jo,⁸¹ Y. Kim,⁸¹ K. Lee,⁸¹ K. S. Lee,⁸¹ S. Lee,⁸¹
J. Lim,⁸¹ S. K. Park,⁸¹ Y. Roh,⁸¹ J. Almond,⁸² J. Kim,⁸² J. S. Kim,⁸² H. Lee,⁸² K. Lee,⁸² K. Nam,⁸² S. B. Oh,⁸²
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I. C. Park,⁸³ G. Ryu,⁸³ Y. Choi,⁸⁴ C. Hwang,⁸⁴ J. Lee,⁸⁴ I. Yu,⁸⁴ V. Dudenias,⁸⁵ A. Juodagalvis,⁸⁵ J. Vaitkus,⁸⁵ I. Ahmed,⁸⁶
Z. A. Ibrahim,⁸⁶ M. A. B. Md Ali,^{86,dd} F. Mohamad Idris,^{86,ee} W. A. T. Wan Abdullah,⁸⁶ M. N. Yusli,⁸⁶ Z. Zolkapli,⁸⁶
H. Castilla-Valdez,⁸⁷ E. De La Cruz-Burelo,⁸⁷ I. Heredia-De La Cruz,^{87,ff} R. Lopez-Fernandez,⁸⁷ J. Mejia Guisao,⁸⁷
A. Sanchez-Hernandez,⁸⁷ S. Carrillo Moreno,⁸⁸ C. Oropeza Barrera,⁸⁸ F. Vazquez Valencia,⁸⁸ I. Pedraza,⁸⁹
H. A. Salazar Ibarguen,⁸⁹ C. Uribe Estrada,⁸⁹ A. Morelos Pineda,⁹⁰ D. Krofcheck,⁹¹ P. H. Butler,⁹² A. Ahmad,⁹³
M. Ahmad,⁹³ Q. Hassan,⁹³ H. R. Hoorani,⁹³ A. Saddique,⁹³ M. A. Shah,⁹³ M. Shoaib,⁹³ M. Waqas,⁹³ H. Bialkowska,⁹⁴
M. Bluj,⁹⁴ B. Boimska,⁹⁴ T. Frueboes,⁹⁴ M. Górski,⁹⁴ M. Kazana,⁹⁴ K. Nawrocki,⁹⁴ K. Romanowska-Rybinska,⁹⁴
M. Szleper,⁹⁴ P. Zalewski,⁹⁴ K. Bunkowski,⁹⁵ A. Byszuk,^{95,gg} K. Doroba,⁹⁵ A. Kalinowski,⁹⁵ M. Konecki,⁹⁵
J. Krolikowski,⁹⁵ M. Misiura,⁹⁵ M. Olszewski,⁹⁵ A. Pyskir,⁹⁵ M. Walczak,⁹⁵ P. Bargassa,⁹⁶ C. Beirão Da Cruz E Silva,⁹⁶
B. Calpas,⁹⁶ A. Di Francesco,⁹⁶ P. Faccioli,⁹⁶ M. Gallinaro,⁹⁶ J. Hollar,⁹⁶ N. Leonardo,⁹⁶ L. Lloret Iglesias,⁹⁶
M. V. Nemallapudi,⁹⁶ J. Seixas,⁹⁶ O. Toldaiev,⁹⁶ D. Vadrucchio,⁹⁶ J. Varela,⁹⁶ S. Afanasiev,⁹⁷ P. Bunin,⁹⁷ M. Gavrilenko,⁹⁷
I. Golutvin,⁹⁷ I. Gorbunov,⁹⁷ A. Kamenev,⁹⁷ V. Karjavin,⁹⁷ A. Lanev,⁹⁷ A. Malakhov,⁹⁷ V. Matveev,^{97,hh,ii} V. Palichik,⁹⁷
V. Perelygin,⁹⁷ S. Shmatov,⁹⁷ S. Shulha,⁹⁷ N. Skatchkov,⁹⁷ V. Smirnov,⁹⁷ N. Voytishin,⁹⁷ A. Zarubin,⁹⁷ Y. Ivanov,⁹⁸

V. Kim,^{98,ji} E. Kuznetsova,^{98,kk} P. Levchenko,⁹⁸ V. Murzin,⁹⁸ V. Oreshkin,⁹⁸ I. Smirnov,⁹⁸ V. Sulimov,⁹⁸ L. Uvarov,⁹⁸ S. Vavilov,⁹⁸ A. Vorobyev,⁹⁸ Yu. Andreev,⁹⁹ A. Dermenev,⁹⁹ S. Gninenko,⁹⁹ N. Golubev,⁹⁹ A. Karneyev,⁹⁹ M. Kirsanov,⁹⁹ N. Krasnikov,⁹⁹ A. Pashenkov,⁹⁹ D. Tliso,⁹⁹ A. Toropin,⁹⁹ V. Epshteyn,¹⁰⁰ V. Gavrilov,¹⁰⁰ N. Lychkovskaya,¹⁰⁰ V. Popov,¹⁰⁰ I. Pozdnyakov,¹⁰⁰ G. Safronov,¹⁰⁰ A. Spiridonov,¹⁰⁰ A. Stepenov,¹⁰⁰ M. Toms,¹⁰⁰ E. Vlasov,¹⁰⁰ A. Zhokin,¹⁰⁰ T. Aushev,¹⁰¹ A. Bylinkin,^{101,ji} R. Chistov,^{102,li} M. Danilov,^{102,li} P. Parygin,¹⁰² D. Philippov,¹⁰² S. Polikarpov,¹⁰² E. Tarkovskii,¹⁰² V. Andreev,¹⁰³ M. Azarkin,^{103,ii} I. Dremin,^{103,ii} M. Kirakosyan,^{103,ii} A. Terkulov,¹⁰³ A. Baskakov,¹⁰⁴ A. Belyaev,¹⁰⁴ E. Boos,¹⁰⁴ M. Dubinin,^{104,mm} L. Dudko,¹⁰⁴ A. Ershov,¹⁰⁴ A. Gribushin,¹⁰⁴ V. Klyukhin,¹⁰⁴ O. Kodolova,¹⁰⁴ I. Lokhtin,¹⁰⁴ I. Miagkov,¹⁰⁴ S. Obraztsov,¹⁰⁴ S. Petrushanko,¹⁰⁴ V. Savrin,¹⁰⁴ A. Snigirev,¹⁰⁴ V. Blinov,^{105,nn} Y. Skovpen,^{105,nn} D. Shtol,^{105,nn} I. Azhgirey,¹⁰⁶ I. Bayshev,¹⁰⁶ S. Bitioukov,¹⁰⁶ D. Elumakhov,¹⁰⁶ V. Kachanov,¹⁰⁶ A. Kalinin,¹⁰⁶ D. Konstantinov,¹⁰⁶ V. Krychkin,¹⁰⁶ V. Petrov,¹⁰⁶ R. Ryutin,¹⁰⁶ A. Sobol,¹⁰⁶ S. Troshin,¹⁰⁶ N. Tyurin,¹⁰⁶ A. Uzunian,¹⁰⁶ A. Volkov,¹⁰⁶ P. Adzic,^{107,oo} P. Cirkovic,¹⁰⁷ D. Devetak,¹⁰⁷ M. Dordevic,¹⁰⁷ J. Milosevic,¹⁰⁷ V. Rekovic,¹⁰⁷ J. Alcaraz Maestre,¹⁰⁸ M. Barrio Luna,¹⁰⁸ M. Cerrada,¹⁰⁸ N. Colino,¹⁰⁸ B. De La Cruz,¹⁰⁸ A. Delgado Peris,¹⁰⁸ A. Escalante Del Valle,¹⁰⁸ C. Fernandez Bedoya,¹⁰⁸ J. P. Fernández Ramos,¹⁰⁸ J. Flix,¹⁰⁸ M. C. Fouz,¹⁰⁸ P. Garcia-Abia,¹⁰⁸ O. Gonzalez Lopez,¹⁰⁸ S. Goy Lopez,¹⁰⁸ J. M. Hernandez,¹⁰⁸ M. I. Josa,¹⁰⁸ A. Pérez-Calero Yzquierdo,¹⁰⁸ J. Puerta Pelayo,¹⁰⁸ A. Quintario Olmeda,¹⁰⁸ I. Redondo,¹⁰⁸ L. Romero,¹⁰⁸ M. S. Soares,¹⁰⁸ A. Álvarez Fernández,¹⁰⁸ J. F. de Trocóniz,¹⁰⁹ M. Missiroli,¹⁰⁹ D. Moran,¹⁰⁹ J. Cuevas,¹¹⁰ C. Erice,¹¹⁰ J. Fernandez Menendez,¹¹⁰ I. Gonzalez Caballero,¹¹⁰ J. R. González Fernández,¹¹⁰ E. Palencia Cortezon,¹¹⁰ S. 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Ingram,¹¹³ H. C. Kaestli,¹¹³ D. Kotlinski,¹¹³ U. Langenegger,¹¹³ T. Rohe,¹¹³ S. A. Wiederkehr,¹¹³ F. Bachmair,¹¹⁴ L. Bäni,¹¹⁴ P. Berger,¹¹⁴ L. Bianchini,¹¹⁴ B. Casal,¹¹⁴ G. Dissertori,¹¹⁴ M. Dittmar,¹¹⁴ M. Donegà,¹¹⁴ C. Grab,¹¹⁴ C. Heidegger,¹¹⁴ D. Hits,¹¹⁴ J. Hoss,¹¹⁴ G. Kasieczka,¹¹⁴ T. Kljnsma,¹¹⁴ W. Lustermann,¹¹⁴ B. Mangano,¹¹⁴ M. Marionneau,¹¹⁴ M. T. Meinhard,¹¹⁴ D. Meister,¹¹⁴ F. Micheli,¹¹⁴ P. Musella,¹¹⁴ F. Nessi-Tedaldi,¹¹⁴ F. Pandolfi,¹¹⁴ J. Pata,¹¹⁴ F. Pauss,¹¹⁴ G. Perrin,¹¹⁴ L. Perrozzi,¹¹⁴ M. Quittnat,¹¹⁴ M. Rossini,¹¹⁴ M. Schönenberger,¹¹⁴ L. Shchutska,¹¹⁴ A. Starodumov,^{114,uu} V. R. Tavolaro,¹¹⁴ K. Theofilatos,¹¹⁴ M. L. Vesterbacka Olsson,¹¹⁴ R. Wallny,¹¹⁴ A. Zagozdinska,^{114,gg} D. H. Zhu,¹¹⁴ T. K. Aarrestad,¹¹⁵ C. Amsler,^{115,vv} L. Caminada,¹¹⁵ M. F. Canelli,¹¹⁵ A. De Cosa,¹¹⁵ S. Donato,¹¹⁵ C. Galloni,¹¹⁵ T. Hreus,¹¹⁵ B. Kilminster,¹¹⁵ J. Ngadiuba,¹¹⁵ D. Pinna,¹¹⁵ G. Rauco,¹¹⁵ P. Robmann,¹¹⁵ D. Salerno,¹¹⁵ C. Seitz,¹¹⁵ A. Zucchetta,¹¹⁵ V. Candelise,¹¹⁶ T. H. Doan,¹¹⁶ Sh. Jain,¹¹⁶ R. Khurana,¹¹⁶ M. Konyushikhin,¹¹⁶ C. M. Kuo,¹¹⁶ W. Lin,¹¹⁶ A. Pozdnyakov,¹¹⁶ S. S. Yu,¹¹⁶ Arun Kumar,¹¹⁷ P. Chang,¹¹⁷ Y. Chao,¹¹⁷ K. F. Chen,¹¹⁷ P. H. Chen,¹¹⁷ F. Fiori,¹¹⁷ W.-S. Hou,¹¹⁷ Y. Hsiung,¹¹⁷ Y. F. Liu,¹¹⁷ R.-S. Lu,¹¹⁷ M. Miñano Moya,¹¹⁷ E. Paganis,¹¹⁷ A. Psallidas,¹¹⁷ J. f. Tsai,¹¹⁷ B. Asavapibhop,¹¹⁸ K. Kovitanggoon,¹¹⁸ G. Singh,¹¹⁸ N. Srimanobhas,¹¹⁸ A. Adiguzel,^{119,ww} F. Boran,¹¹⁹ S. Damarseckin,¹¹⁹ Z. S. Demiroglu,¹¹⁹ C. Dozen,¹¹⁹ E. Eskut,¹¹⁹ S. Girgis,¹¹⁹ G. Gokbulut,¹¹⁹ Y. Guler,¹¹⁹ I. Hos,^{119,xx} E. E. Kangal,^{119,yy} O. Kara,¹¹⁹ A. Kayis Topaksu,¹¹⁹ U. Kiminsu,¹¹⁹ M. Oglakci,¹¹⁹ G. Onengut,^{119,zz} K. Ozdemir,^{119,aaa} S. Ozturk,^{119,bbb} A. Polatoz,¹¹⁹ B. Tali,^{119,ccc} S. Turkcapar,¹¹⁹ I. S. Zorbakir,¹¹⁹ C. Zorbilmez,¹¹⁹ B. Bilin,¹²⁰ G. Karapinar,^{120,ddd} K. Ocalan,^{120,eee} M. Yalvac,¹²⁰ M. Zeyrek,¹²⁰ E. Gülmez,¹²¹ M. Kaya,^{121,fff} O. Kaya,^{121,ggg} S. Tekten,¹²¹ E. A. Yetkin,^{121,hhh} M. N. Agaras,¹²² S. Atay,¹²²

A. Cakir,¹²² K. Cankocak,¹²² B. Grynyov,¹²³ L. Levchuk,¹²⁴ P. Sorokin,¹²⁴ R. Aggleton,¹²⁵ F. Ball,¹²⁵ L. Beck,¹²⁵ J. J. Brooke,¹²⁵ D. Burns,¹²⁵ E. Clement,¹²⁵ D. Cussans,¹²⁵ O. Davignon,¹²⁵ H. Flacher,¹²⁵ J. Goldstein,¹²⁵ M. Grimes,¹²⁵ G. P. Heath,¹²⁵ H. F. Heath,¹²⁵ J. Jacob,¹²⁵ L. Kreczko,¹²⁵ C. Lucas,¹²⁵ D. M. Newbold,^{125,iii} S. Paramesvaran,¹²⁵ A. Poll,¹²⁵ T. Sakuma,¹²⁵ S. Seif El Nasr-storey,¹²⁵ D. Smith,¹²⁵ V. J. Smith,¹²⁵ K. W. Bell,¹²⁶ A. Belyaev,^{126,iii} C. Brew,¹²⁶ R. M. Brown,¹²⁶ L. Calligaris,¹²⁶ D. Cieri,¹²⁶ D. J. A. Cockerill,¹²⁶ J. A. Coughlan,¹²⁶ K. Harder,¹²⁶ S. Harper,¹²⁶ E. Olaiya,¹²⁶ D. Petyt,¹²⁶ C. H. Shepherd-Themistocleous,¹²⁶ A. Thea,¹²⁶ I. R. Tomalin,¹²⁶ T. Williams,¹²⁶ M. Baber,¹²⁷ R. Bainbridge,¹²⁷ S. Breeze,¹²⁷ O. Buchmuller,¹²⁷ A. Bundock,¹²⁷ S. Casasso,¹²⁷ M. Citron,¹²⁷ D. Colling,¹²⁷ L. Corpe,¹²⁷ P. Dauncey,¹²⁷ G. Davies,¹²⁷ A. De Wit,¹²⁷ M. Della Negra,¹²⁷ R. Di Maria,¹²⁷ P. Dunne,¹²⁷ A. Elwood,¹²⁷ D. Futyan,¹²⁷ Y. Haddad,¹²⁷ G. Hall,¹²⁷ G. 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Laird,¹³³ G. Landsberg,¹³³ Z. Mao,¹³³ M. Narain,¹³³ S. Piperov,¹³³ S. Sagir,¹³³ R. Syarif,¹³³ D. Yu,¹³³ R. Band,¹³⁴ C. Brainerd,¹³⁴ D. Burns,¹³⁴ M. Calderon De La Barca Sanchez,¹³⁴ M. Chertok,¹³⁴ J. Conway,¹³⁴ R. Conway,¹³⁴ P. T. Cox,¹³⁴ R. Erbacher,¹³⁴ C. Flores,¹³⁴ G. Funk,¹³⁴ M. Gardner,¹³⁴ W. Ko,¹³⁴ R. Lander,¹³⁴ C. Mclean,¹³⁴ M. Mulhearn,¹³⁴ D. Pellett,¹³⁴ J. Pilot,¹³⁴ S. Shalhout,¹³⁴ M. Shi,¹³⁴ J. Smith,¹³⁴ M. Squires,¹³⁴ D. Stolp,¹³⁴ K. Tos,¹³⁴ M. Tripathi,¹³⁴ Z. Wang,¹³⁴ M. Bachtis,¹³⁵ C. Bravo,¹³⁵ R. Cousins,¹³⁵ A. Dasgupta,¹³⁵ A. Florent,¹³⁵ J. Hauser,¹³⁵ M. Ignatenko,¹³⁵ N. Mccoll,¹³⁵ D. Saltzberg,¹³⁵ C. Schnaible,¹³⁵ V. Valuev,¹³⁵ E. Bouvier,¹³⁶ K. Burt,¹³⁶ R. Clare,¹³⁶ J. Ellison,¹³⁶ J. W. Gary,¹³⁶ S. M. A. Ghiasi Shirazi,¹³⁶ G. Hanson,¹³⁶ J. Heilman,¹³⁶ P. Jandir,¹³⁶ E. Kennedy,¹³⁶ F. Lacroix,¹³⁶ O. R. Long,¹³⁶ M. Olmedo Negrete,¹³⁶ M. I. Paneva,¹³⁶ A. Shrinivas,¹³⁶ W. Si,¹³⁶ L. Wang,¹³⁶ H. Wei,¹³⁶ S. Wimpenny,¹³⁶ B. R. Yates,¹³⁶ J. G. Branson,¹³⁷ S. Cittolin,¹³⁷ M. Derdzinski,¹³⁷ B. Hashemi,¹³⁷ A. Holzner,¹³⁷ D. Klein,¹³⁷ G. Kole,¹³⁷ V. Krutelyov,¹³⁷ J. Letts,¹³⁷ I. Macneill,¹³⁷ M. Masciovecchio,¹³⁷ D. Olivito,¹³⁷ S. Padhi,¹³⁷ M. Pieri,¹³⁷ M. Sani,¹³⁷ V. Sharma,¹³⁷ S. Simon,¹³⁷ M. Tadel,¹³⁷ A. Vartak,¹³⁷ S. Wasserbaech,^{137,iii} J. Wood,¹³⁷ F. Würthwein,¹³⁷ A. Yagil,¹³⁷ G. Zevi Della Porta,¹³⁷ N. Amin,¹³⁸ R. Bhandari,¹³⁸ J. Bradmiller-Feld,¹³⁸ C. Campagnari,¹³⁸ A. Dishaw,¹³⁸ V. Dutta,¹³⁸ M. Franco Sevilla,¹³⁸ C. George,¹³⁸ F. Golf,¹³⁸ L. Gouskos,¹³⁸ J. Gran,¹³⁸ R. Heller,¹³⁸ J. Incandela,¹³⁸ S. D. Mullin,¹³⁸ A. Ovcharova,¹³⁸ H. Qu,¹³⁸ J. Richman,¹³⁸ D. Stuart,¹³⁸ I. Suarez,¹³⁸ J. Yoo,¹³⁸ D. Anderson,¹³⁹ J. Bendavid,¹³⁹ A. Bornheim,¹³⁹ J. M. Lawhorn,¹³⁹ H. B. Newman,¹³⁹ T. Nguyen,¹³⁹ C. Pena,¹³⁹ M. Spiropulu,¹³⁹ J. R. Vlimant,¹³⁹ S. Xie,¹³⁹ Z. Zhang,¹³⁹ R. Y. Zhu,¹³⁹ M. B. Andrews,¹⁴⁰ T. Ferguson,¹⁴⁰ T. Mudholkar,¹⁴⁰ M. Paulini,¹⁴⁰ J. Russ,¹⁴⁰ M. Sun,¹⁴⁰ H. Vogel,¹⁴⁰ I. Vorobiev,¹⁴⁰ M. Weinberg,¹⁴⁰ J. P. Cumalat,¹⁴¹ W. T. Ford,¹⁴¹ F. Jensen,¹⁴¹ A. Johnson,¹⁴¹ M. Krohn,¹⁴¹ S. Leontsinis,¹⁴¹ T. Mulholland,¹⁴¹ K. Stenson,¹⁴¹ S. R. Wagner,¹⁴¹ J. Alexander,¹⁴² J. Chaves,¹⁴² J. Chu,¹⁴² S. Dittmer,¹⁴² K. McDermott,¹⁴² N. Mirman,¹⁴² J. R. Patterson,¹⁴² A. Rinkevicius,¹⁴² A. Ryd,¹⁴² L. Skinnari,¹⁴² L. Soffi,¹⁴² S. M. Tan,¹⁴² Z. Tao,¹⁴² J. Thom,¹⁴² J. Tucker,¹⁴² P. Wittich,¹⁴² M. Zientek,¹⁴² S. Abdullin,¹⁴³ M. Albrow,¹⁴³ G. Apollinari,¹⁴³ A. Apresyan,¹⁴³ A. Apyan,¹⁴³ S. Banerjee,¹⁴³ L. A. T. Bauerdick,¹⁴³ A. Beretvas,¹⁴³ J. Berryhill,¹⁴³ P. C. Bhat,¹⁴³ G. Bolla,¹⁴³ K. Burkett,¹⁴³ J. N. Butler,¹⁴³ A. Canepa,¹⁴³ G. B. Cerati,¹⁴³ H. W. K. Cheung,¹⁴³ F. Chlebana,¹⁴³ M. Cremonesi,¹⁴³ J. Duarte,¹⁴³ V. D. Elvira,¹⁴³ J. Freeman,¹⁴³ Z. Gecse,¹⁴³ E. Gottschalk,¹⁴³ L. Gray,¹⁴³ D. Green,¹⁴³ S. Grünendahl,¹⁴³ O. Gutsche,¹⁴³ R. M. Harris,¹⁴³ S. Hasegawa,¹⁴³ J. Hirschauer,¹⁴³ Z. Hu,¹⁴³ B. Jayatilaka,¹⁴³ S. Jindariani,¹⁴³ M. Johnson,¹⁴³ U. Joshi,¹⁴³ B. Klima,¹⁴³ B. Kreis,¹⁴³ S. Lammel,¹⁴³ D. Lincoln,¹⁴³ R. Lipton,¹⁴³ M. Liu,¹⁴³ T. Liu,¹⁴³ R. Lopes De Sá,¹⁴³ J. Lykken,¹⁴³ K. Maeshima,¹⁴³ N. Magini,¹⁴³ J. M. Marraffino,¹⁴³ S. Maruyama,¹⁴³ D. Mason,¹⁴³ P. McBride,¹⁴³ P. Merkel,¹⁴³ S. Mrenna,¹⁴³ S. Nahn,¹⁴³ V. O'Dell,¹⁴³ K. Pedro,¹⁴³ O. Prokofyev,¹⁴³ G. Rakness,¹⁴³ L. Ristori,¹⁴³ B. Schneider,¹⁴³ E. Sexton-Kennedy,¹⁴³ A. Soha,¹⁴³ W. J. Spalding,¹⁴³ L. Spiegel,¹⁴³ S. Stoynev,¹⁴³ J. Strait,¹⁴³ N. Strobbe,¹⁴³ L. Taylor,¹⁴³ S. Tkaczyk,¹⁴³ N. V. Tran,¹⁴³ L. Uplegger,¹⁴³ E. W. Vaandering,¹⁴³ C. Vernieri,¹⁴³ M. Verzocchi,¹⁴³ R. Vidal,¹⁴³ M. Wang,¹⁴³ H. A. Weber,¹⁴³ A. Whitbeck,¹⁴³ D. Acosta,¹⁴⁴ P. Avery,¹⁴⁴ P. Bortignon,¹⁴⁴ A. Brinkerhoff,¹⁴⁴ A. Carnes,¹⁴⁴ M. Carver,¹⁴⁴ D. Curry,¹⁴⁴ S. Das,¹⁴⁴ R. D. Field,¹⁴⁴ I. K. Furic,¹⁴⁴ J. Konigsberg,¹⁴⁴ A. Korytov,¹⁴⁴ K. Kotov,¹⁴⁴ P. Ma,¹⁴⁴ K. Matchev,¹⁴⁴ H. Mei,¹⁴⁴ G. Mitselmakher,¹⁴⁴ D. Rank,¹⁴⁴ D. Sperka,¹⁴⁴ N. Terentyev,¹⁴⁴ L. Thomas,¹⁴⁴ J. Wang,¹⁴⁴ S. Wang,¹⁴⁴

J. Yelton,¹⁴⁴ Y. R. Joshi,¹⁴⁵ S. Linn,¹⁴⁵ P. Markowitz,¹⁴⁵ G. Martinez,¹⁴⁵ J. L. Rodriguez,¹⁴⁵ A. Ackert,¹⁴⁶ T. Adams,¹⁴⁶ A. Askew,¹⁴⁶ S. Hagopian,¹⁴⁶ V. Hagopian,¹⁴⁶ K. F. Johnson,¹⁴⁶ T. Kolberg,¹⁴⁶ T. Perry,¹⁴⁶ H. Prosper,¹⁴⁶ A. Santra,¹⁴⁶ R. Yohay,¹⁴⁶ M. M. Baarmand,¹⁴⁷ V. Bhopatkar,¹⁴⁷ S. Colafranceschi,¹⁴⁷ M. Hohlmann,¹⁴⁷ D. Noonan,¹⁴⁷ T. Roy,¹⁴⁷ F. Yumiceva,¹⁴⁷ M. R. Adams,¹⁴⁸ L. Apanasevich,¹⁴⁸ D. Berry,¹⁴⁸ R. R. Betts,¹⁴⁸ R. Cavanaugh,¹⁴⁸ X. Chen,¹⁴⁸ O. Evdokimov,¹⁴⁸ C. E. Gerber,¹⁴⁸ D. A. Hangal,¹⁴⁸ D. J. Hofman,¹⁴⁸ K. Jung,¹⁴⁸ J. Kamin,¹⁴⁸ I. D. Sandoval Gonzalez,¹⁴⁸ M. B. Tonjes,¹⁴⁸ H. Trauger,¹⁴⁸ N. Varelas,¹⁴⁸ H. Wang,¹⁴⁸ Z. Wu,¹⁴⁸ J. Zhang,¹⁴⁸ B. Bilki,^{149,mmm} W. Clarida,¹⁴⁹ K. Dilsiz,^{149,nnn} S. Durgut,¹⁴⁹ R. P. Gandrajula,¹⁴⁹ M. Haytmyradov,¹⁴⁹ V. Khristenko,¹⁴⁹ J.-P. Merlo,¹⁴⁹ H. Mermerkaya,^{149,ooo} A. Mestvirishvili,¹⁴⁹ A. Moeller,¹⁴⁹ J. Nachtman,¹⁴⁹ H. Ogul,^{149,ppp} Y. Onel,¹⁴⁹ F. Ozok,^{149,qqq} A. Penzo,¹⁴⁹ C. Snyder,¹⁴⁹ E. Tiras,¹⁴⁹ J. Wetzel,¹⁴⁹ K. Yi,¹⁴⁹ B. Blumenfeld,¹⁵⁰ A. Cocoros,¹⁵⁰ N. Eminizer,¹⁵⁰ D. Fehling,¹⁵⁰ L. Feng,¹⁵⁰ A. V. Gritsan,¹⁵⁰ P. Maksimovic,¹⁵⁰ J. Roskes,¹⁵⁰ U. Sarica,¹⁵⁰ M. Swartz,¹⁵⁰ M. Xiao,¹⁵⁰ C. You,¹⁵⁰ A. Al-bataineh,¹⁵¹ P. Baringer,¹⁵¹ A. Bean,¹⁵¹ S. Boren,¹⁵¹ J. Bowen,¹⁵¹ J. Castle,¹⁵¹ S. Khalil,¹⁵¹ A. Kropivnitskaya,¹⁵¹ D. Majumder,¹⁵¹ W. Mcbrayer,¹⁵¹ M. Murray,¹⁵¹ C. Royon,¹⁵¹ S. Sanders,¹⁵¹ E. Schmitz,¹⁵¹ R. Stringer,¹⁵¹ J. D. Tapia Takaki,¹⁵¹ Q. Wang,¹⁵¹ A. Ivanov,¹⁵² K. Kaadze,¹⁵² Y. Maravin,¹⁵² A. Mohammadi,¹⁵² L. K. Saini,¹⁵² N. Skhirtladze,¹⁵² S. Toda,¹⁵² F. Rebassoo,¹⁵³ D. Wright,¹⁵³ C. Anelli,¹⁵⁴ A. Baden,¹⁵⁴ O. Baron,¹⁵⁴ A. Belloni,¹⁵⁴ B. Calvert,¹⁵⁴ S. C. Eno,¹⁵⁴ C. Ferraioli,¹⁵⁴ N. J. Hadley,¹⁵⁴ S. Jabeen,¹⁵⁴ G. Y. Jeng,¹⁵⁴ R. G. Kellogg,¹⁵⁴ J. Kunkle,¹⁵⁴ A. C. Mignerey,¹⁵⁴ F. Ricci-Tam,¹⁵⁴ Y. H. Shin,¹⁵⁴ A. Skuja,¹⁵⁴ S. C. Tonwar,¹⁵⁴ D. Abercrombie,¹⁵⁵ B. Allen,¹⁵⁵ V. Azzolini,¹⁵⁵ R. Barbieri,¹⁵⁵ A. Baty,¹⁵⁵ R. Bi,¹⁵⁵ S. Brandt,¹⁵⁵ W. Busza,¹⁵⁵ I. A. Cali,¹⁵⁵ M. D'Alfonso,¹⁵⁵ Z. Demiragli,¹⁵⁵ G. Gomez Ceballos,¹⁵⁵ M. Goncharov,¹⁵⁵ D. Hsu,¹⁵⁵ Y. Iiyama,¹⁵⁵ G. M. Innocenti,¹⁵⁵ M. Klute,¹⁵⁵ D. Kovalskyi,¹⁵⁵ Y. S. Lai,¹⁵⁵ Y.-J. Lee,¹⁵⁵ A. Levin,¹⁵⁵ P. D. Luckey,¹⁵⁵ B. Maier,¹⁵⁵ A. C. Marini,¹⁵⁵ C. McGinn,¹⁵⁵ C. Mironov,¹⁵⁵ S. Narayanan,¹⁵⁵ X. Niu,¹⁵⁵ C. Paus,¹⁵⁵ C. Roland,¹⁵⁵ G. Roland,¹⁵⁵ J. Salfeld-Nebgen,¹⁵⁵ G. S. F. Stephans,¹⁵⁵ K. Tatar,¹⁵⁵ D. Velicanu,¹⁵⁵ J. Wang,¹⁵⁵ T. W. Wang,¹⁵⁵ B. Wyslouch,¹⁵⁵ A. C. Benvenuti,¹⁵⁶ R. M. Chatterjee,¹⁵⁶ A. Evans,¹⁵⁶ P. Hansen,¹⁵⁶ S. Kalafut,¹⁵⁶ Y. Kubota,¹⁵⁶ Z. Lesko,¹⁵⁶ J. Mans,¹⁵⁶ S. Nourbakhsh,¹⁵⁶ N. Ruckstuhl,¹⁵⁶ R. Rusack,¹⁵⁶ J. Turkewitz,¹⁵⁶ J. G. Acosta,¹⁵⁷ S. Oliveros,¹⁵⁷ E. Avdeeva,¹⁵⁸ K. Bloom,¹⁵⁸ D. R. Claes,¹⁵⁸ C. Fangmeier,¹⁵⁸ R. Gonzalez Suarez,¹⁵⁸ R. Kamalieddin,¹⁵⁸ I. Kravchenko,¹⁵⁸ J. Monroy,¹⁵⁸ J. E. Siado,¹⁵⁸ G. R. Snow,¹⁵⁸ B. Stieger,¹⁵⁸ M. Alyari,¹⁵⁹ J. Dolen,¹⁵⁹ A. Godshalk,¹⁵⁹ C. Harrington,¹⁵⁹ I. Iashvili,¹⁵⁹ D. Nguyen,¹⁵⁹ A. Parker,¹⁵⁹ S. Rappoccio,¹⁵⁹ B. Roozbahani,¹⁵⁹ G. Alverson,¹⁶⁰ E. Barberis,¹⁶⁰ A. Hortiangtham,¹⁶⁰ A. Massironi,¹⁶⁰ D. M. Morse,¹⁶⁰ D. Nash,¹⁶⁰ T. Orimoto,¹⁶⁰ R. Teixeira De Lima,¹⁶⁰ D. Trocino,¹⁶⁰ R.-J. Wang,¹⁶⁰ D. Wood,¹⁶⁰ S. Bhattacharya,¹⁶¹ O. Charaf,¹⁶¹ K. A. Hahn,¹⁶¹ N. Mucia,¹⁶¹ N. Odell,¹⁶¹ B. Pollack,¹⁶¹ M. H. Schmitt,¹⁶¹ K. Sung,¹⁶¹ M. Trovato,¹⁶¹ M. Velasco,¹⁶¹ N. Dev,¹⁶² M. Hildreth,¹⁶² K. Hurtado Anampa,¹⁶² C. Jessop,¹⁶² D. J. Karmgard,¹⁶² N. Kellams,¹⁶² K. Lannon,¹⁶² N. Loukas,¹⁶² N. Marinelli,¹⁶² F. Meng,¹⁶² C. Mueller,¹⁶² Y. Musienko,^{162,hh} M. Planer,¹⁶² A. Reinsvold,¹⁶² R. Ruchti,¹⁶² G. Smith,¹⁶² S. Taroni,¹⁶² M. Wayne,¹⁶² M. Wolf,¹⁶² A. Woodard,¹⁶² J. Alimena,¹⁶³ L. Antonelli,¹⁶³ B. Bylsma,¹⁶³ L. S. Durkin,¹⁶³ S. Flowers,¹⁶³ B. Francis,¹⁶³ A. Hart,¹⁶³ C. Hill,¹⁶³ W. Ji,¹⁶³ B. Liu,¹⁶³ W. Luo,¹⁶³ D. Puigh,¹⁶³ B. L. Winer,¹⁶³ H. W. Wulsin,¹⁶³ A. Benaglia,¹⁶⁴ S. Cooperstein,¹⁶⁴ O. Driga,¹⁶⁴ P. Elmer,¹⁶⁴ J. Hardenbrook,¹⁶⁴ P. Hebda,¹⁶⁴ S. Higginbotham,¹⁶⁴ D. Lange,¹⁶⁴ J. Luo,¹⁶⁴ D. Marlow,¹⁶⁴ K. Mei,¹⁶⁴ I. Ojalvo,¹⁶⁴ J. Olsen,¹⁶⁴ C. Palmer,¹⁶⁴ P. Piroué,¹⁶⁴ D. Stickland,¹⁶⁴ A. Svyatkovskiy,¹⁶⁴ C. Tully,¹⁶⁴ S. Malik,¹⁶⁵ S. Norberg,¹⁶⁵ A. Barker,¹⁶⁶ V. E. Barnes,¹⁶⁶ S. Folgueras,¹⁶⁶ L. Gutay,¹⁶⁶ M. K. Jha,¹⁶⁶ M. Jones,¹⁶⁶ A. W. Jung,¹⁶⁶ A. Khatiwada,¹⁶⁶ D. H. Miller,¹⁶⁶ N. Neumeister,¹⁶⁶ C. C. Peng,¹⁶⁶ J. F. Schulte,¹⁶⁶ J. Sun,¹⁶⁶ F. Wang,¹⁶⁶ W. Xie,¹⁶⁶ T. Cheng,¹⁶⁷ N. Parashar,¹⁶⁷ J. Stupak,¹⁶⁷ A. Adair,¹⁶⁸ B. Akgun,¹⁶⁸ Z. Chen,¹⁶⁸ K. M. Ecklund,¹⁶⁸ F. J. M. Geurts,¹⁶⁸ M. Guilbaud,¹⁶⁸ W. Li,¹⁶⁸ B. Michlin,¹⁶⁸ M. Northup,¹⁶⁸ B. P. Padley,¹⁶⁸ J. Roberts,¹⁶⁸ J. Rorie,¹⁶⁸ Z. Tu,¹⁶⁸ J. Zabel,¹⁶⁸ A. Bodek,¹⁶⁹ P. de Barbaro,¹⁶⁹ R. Demina,¹⁶⁹ Y. t. Duh,¹⁶⁹ T. Ferbel,¹⁶⁹ M. Galanti,¹⁶⁹ A. Garcia-Bellido,¹⁶⁹ J. Han,¹⁶⁹ O. Hindrichs,¹⁶⁹ A. Khukhunaishvili,¹⁶⁹ K. H. Lo,¹⁶⁹ P. Tan,¹⁶⁹ M. Verzetti,¹⁶⁹ R. Ciesielski,¹⁷⁰ K. Goulianos,¹⁷⁰ C. Mesropian,¹⁷⁰ A. Agapitos,¹⁷¹ J. P. Chou,¹⁷¹ Y. Gershtein,¹⁷¹ T. A. Gómez Espinosa,¹⁷¹ E. Halkiadakis,¹⁷¹ M. Heindl,¹⁷¹ E. Hughes,¹⁷¹ S. Kaplan,¹⁷¹ R. Kunnawalkam Elayavalli,¹⁷¹ S. Kyriacou,¹⁷¹ A. Lath,¹⁷¹ R. Montalvo,¹⁷¹ K. Nash,¹⁷¹ M. Osherson,¹⁷¹ H. Saka,¹⁷¹ S. Salur,¹⁷¹ S. Schnetzer,¹⁷¹ D. Sheffield,¹⁷¹ S. Somalwar,¹⁷¹ R. Stone,¹⁷¹ S. Thomas,¹⁷¹ P. Thomassen,¹⁷¹ M. Walker,¹⁷¹ A. G. Delannoy,¹⁷² M. Foerster,¹⁷² J. Heideman,¹⁷² G. Riley,¹⁷² K. Rose,¹⁷² S. Spanier,¹⁷² K. Thapa,¹⁷² O. Bouhali,^{173,mrr} A. Castaneda Hernandez,^{173,mrr} A. Celik,¹⁷³ M. Dalchenko,¹⁷³ M. De Mattia,¹⁷³ A. Delgado,¹⁷³ S. Dildick,¹⁷³ R. Eusebi,¹⁷³ J. Gilmore,¹⁷³ T. Huang,¹⁷³ T. Kamon,^{173,sss} R. Mueller,¹⁷³ Y. Pakhotin,¹⁷³ R. Patel,¹⁷³ A. Perloff,¹⁷³ L. Perniè,¹⁷³ D. Rathjens,¹⁷³ A. Safonov,¹⁷³ A. Tatarinov,¹⁷³ K. A. Ulmer,¹⁷³ N. Akchurin,¹⁷⁴ J. Damgov,¹⁷⁴ F. De Guio,¹⁷⁴ P. R. Duerdo,¹⁷⁴ J. Faulkner,¹⁷⁴ E. Gurpinar,¹⁷⁴ S. Kunori,¹⁷⁴ K. Lamichhane,¹⁷⁴ S. W. Lee,¹⁷⁴ T. Libeiro,¹⁷⁴ T. Peltola,¹⁷⁴ S. Undleeb,¹⁷⁴ I. Volobouev,¹⁷⁴ Z. Wang,¹⁷⁴ S. Greene,¹⁷⁵

A. Gurrola,¹⁷⁵ R. Janjam,¹⁷⁵ W. Johns,¹⁷⁵ C. Maguire,¹⁷⁵ A. Melo,¹⁷⁵ H. Ni,¹⁷⁵ P. Sheldon,¹⁷⁵ S. Tuo,¹⁷⁵ J. Velkovska,¹⁷⁵ Q. Xu,¹⁷⁵ M. W. Arenton,¹⁷⁶ P. Barria,¹⁷⁶ B. Cox,¹⁷⁶ R. Hirosky,¹⁷⁶ A. Ledovskoy,¹⁷⁶ H. Li,¹⁷⁶ C. Neu,¹⁷⁶ T. Sinthuprasith,¹⁷⁶ X. Sun,¹⁷⁶ Y. Wang,¹⁷⁶ E. Wolfe,¹⁷⁶ F. Xia,¹⁷⁶ C. Clarke,¹⁷⁷ R. Harr,¹⁷⁷ P. E. Karchin,¹⁷⁷ J. Sturdy,¹⁷⁷ S. Zaleski,¹⁷⁷ J. Buchanan,¹⁷⁸ C. Caillol,¹⁷⁸ S. Dasu,¹⁷⁸ L. Dodd,¹⁷⁸ S. Duric,¹⁷⁸ B. Gomber,¹⁷⁸ M. Grothe,¹⁷⁸ M. Herndon,¹⁷⁸ A. Hervé,¹⁷⁸ U. Hussain,¹⁷⁸ P. Klabbers,¹⁷⁸ A. Lanaro,¹⁷⁸ A. Levine,¹⁷⁸ K. Long,¹⁷⁸ R. Loveless,¹⁷⁸ G. A. Pierro,¹⁷⁸ G. Polese,¹⁷⁸ T. Ruggles,¹⁷⁸ A. Savin,¹⁷⁸ N. Smith,¹⁷⁸ W. H. Smith,¹⁷⁸ D. Taylor,¹⁷⁸ and N. Woods¹⁷⁸

(CMS Collaboration)

¹*Yerevan Physics Institute, Yerevan, Armenia*

²*Institut für Hochenergiephysik, Wien, Austria*

³*Institute for Nuclear Problems, Minsk, Belarus*

⁴*Universiteit Antwerpen, Antwerpen, Belgium*

⁵*Vrije Universiteit Brussel, Brussel, Belgium*

⁶*Université Libre de Bruxelles, Bruxelles, Belgium*

⁷*Ghent University, Ghent, Belgium*

⁸*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*

⁹*Université de Mons, Mons, Belgium*

¹⁰*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

¹¹*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

¹²*Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil*

^{12a}*Universidade Estadual Paulista, São Paulo, Brazil*

^{12b}*Universidade Federal do ABC, São Paulo, Brazil*

¹³*Institute for Nuclear Research and Nuclear Energy of Bulgaria Academy of Sciences*

¹⁴*University of Sofia, Sofia, Bulgaria*

¹⁵*Beihang University, Beijing, China*

¹⁶*Institute of High Energy Physics, Beijing, China*

¹⁷*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

¹⁸*Universidad de Los Andes, Bogota, Colombia*

¹⁹*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*

²⁰*University of Split, Faculty of Science, Split, Croatia*

²¹*Institute Rudjer Boskovic, Zagreb, Croatia*

²²*University of Cyprus, Nicosia, Cyprus*

²³*Charles University, Prague, Czech Republic*

²⁴*Universidad San Francisco de Quito, Quito, Ecuador*

²⁵*Academy of Scientific Research and Technology of the Arab Republic of Egypt,*

Egyptian Network of High Energy Physics, Cairo, Egypt

²⁶*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

²⁷*Department of Physics, University of Helsinki, Helsinki, Finland*

²⁸*Helsinki Institute of Physics, Helsinki, Finland*

²⁹*Lappeenranta University of Technology, Lappeenranta, Finland*

³⁰*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

³¹*Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France*

³²*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*

³³*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*

³⁴*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*

³⁵*Georgian Technical University, Tbilisi, Georgia*

³⁶*Tbilisi State University, Tbilisi, Georgia*

³⁷*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*

³⁸*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*

³⁹*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*

⁴⁰*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

⁴¹*University of Hamburg, Hamburg, Germany*

⁴²*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

⁴³*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*

⁴⁴*National and Kapodistrian University of Athens, Athens, Greece*

⁴⁵*University of Ioánnina, Ioánnina, Greece*

- ⁴⁶MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- ⁴⁷Wigner Research Centre for Physics, Budapest, Hungary
- ⁴⁸Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ⁴⁹Institute of Physics, University of Debrecen, Debrecen, Hungary
- ⁵⁰Indian Institute of Science (IISc), Bangalore, India
- ⁵¹National Institute of Science Education and Research, Bhubaneswar, India
- ⁵²Panjab University, Chandigarh, India
- ⁵³University of Delhi, Delhi, India
- ⁵⁴Saha Institute of Nuclear Physics, HBNI, Kolkata, India
- ⁵⁵Indian Institute of Technology Madras, Madras, India
- ⁵⁶Bhabha Atomic Research Centre, Mumbai, India
- ⁵⁷Tata Institute of Fundamental Research-A, Mumbai, India
- ⁵⁸Tata Institute of Fundamental Research-B, Mumbai, India
- ⁵⁹Indian Institute of Science Education and Research (IISER), Pune, India
- ⁶⁰Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
- ⁶¹University College Dublin, Dublin, Ireland
- ⁶²INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
- ^{62a}INFN Sezione di Bari, Bari, Italy
- ^{62b}Università di Bari, Bari, Italy
- ^{62c}Politecnico di Bari, Bari, Italy
- ⁶³INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
- ^{63a}INFN Sezione di Bologna, Bologna, Italy
- ^{63b}Università di Bologna, Bologna, Italy
- ⁶⁴INFN Sezione di Catania, Università di Catania, Catania, Italy
- ^{64a}INFN Sezione di Catania, Catania, Italy
- ^{64b}Università di Catania, Catania, Italy
- ⁶⁵INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
- ^{65a}INFN Sezione di Firenze, Firenze, Italy
- ^{65b}Università di Firenze, Firenze, Italy
- ⁶⁶INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁶⁷INFN Sezione di Genova, Università di Genova, Genova, Italy
- ^{67a}INFN Sezione di Genova, Genova, Italy
- ^{67b}Università di Genova, Genova, Italy
- ^{68a}INFN Sezione di Milano-Bicocca, Genova, Italy
- ^{68b}Università di Milano-Bicocca, Genova, Italy
- ⁶⁹INFN Sezione di Napoli, Università di Napoli 'Federico II', Napoli, Italy, Università della Basilicata, Potenza, Italy, Università G. Marconi, Roma, Italy
- ^{69a}INFN Sezione di Napoli, Roma, Italy
- ^{69b}Università di Napoli 'Federico II', Roma, Italy
- ^{69c}Università della Basilicata, Roma, Italy
- ^{69d}Università G. Marconi, Roma, Italy
- ⁷⁰INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy
- ^{70a}INFN Sezione di Padova, Trento, Italy
- ^{70b}Università di Padova, Trento, Italy
- ^{70c}Università di Trento, Trento, Italy
- ⁷¹INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- ^{71a}INFN Sezione di Pavia, Pavia, Italy
- ^{71b}Università di Pavia, Pavia, Italy
- ⁷²INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
- ^{72a}INFN Sezione di Perugia, Perugia, Italy
- ^{72b}Università di Perugia, Perugia, Italy
- ⁷³INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
- ^{73a}INFN Sezione di Pisa, Pisa, Italy
- ^{73b}Università di Pisa, Pisa, Italy
- ^{73c}Scuola Normale Superiore di Pisa, Pisa, Italy
- ^{74a}INFN Sezione di Roma, Pisa, Italy
- ^{74b}Sapienza Università di Roma, Pisa, Italy
- ⁷⁵INFN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy
- ^{75a}INFN Sezione di Torino, Novara, Italy
- ^{75b}Università di Torino, Novara, Italy

- ^{75c}*Università del Piemonte Orientale, Novara, Italy*
⁷⁶*INFN Sezione di Trieste, Università di Trieste, Trieste, Italy*
^{76a}*INFN Sezione di Trieste, Trieste, Italy*
^{76b}*Università di Trieste, Trieste, Italy*
⁷⁷*Kyungpook National University, Daegu, Korea*
⁷⁸*Chonbuk National University, Jeonju, Korea*
⁷⁹*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
⁸⁰*Hanyang University, Seoul, Korea*
⁸¹*Korea University, Seoul, Korea*
⁸²*Seoul National University, Seoul, Korea*
⁸³*University of Seoul, Seoul, Korea*
⁸⁴*Sungkyunkwan University, Suwon, Korea*
⁸⁵*Vilnius University, Vilnius, Lithuania*
⁸⁶*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
⁸⁷*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
⁸⁸*Universidad Iberoamericana, Mexico City, Mexico*
⁸⁹*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
⁹⁰*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
⁹¹*University of Auckland, Auckland, New Zealand*
⁹²*University of Canterbury, Christchurch, New Zealand*
⁹³*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
⁹⁴*National Centre for Nuclear Research, Swierk, Poland*
⁹⁵*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
⁹⁶*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
⁹⁷*Joint Institute for Nuclear Research, Dubna, Russia*
⁹⁸*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
⁹⁹*Institute for Nuclear Research, Moscow, Russia*
¹⁰⁰*Institute for Theoretical and Experimental Physics, Moscow, Russia*
¹⁰¹*Moscow Institute of Physics and Technology, Moscow, Russia*
¹⁰²*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*
¹⁰³*P.N. Lebedev Physical Institute, Moscow, Russia*
¹⁰⁴*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
¹⁰⁵*Novosibirsk State University (NSU), Novosibirsk, Russia*
¹⁰⁶*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*
¹⁰⁷*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
¹⁰⁸*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
¹⁰⁹*Universidad Autónoma de Madrid, Madrid, Spain*
¹¹⁰*Universidad de Oviedo, Oviedo, Spain*
¹¹¹*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
¹¹²*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
¹¹³*Paul Scherrer Institut, Villigen, Switzerland*
¹¹⁴*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*
¹¹⁵*Universität Zürich, Zurich, Switzerland*
¹¹⁶*National Central University, Chung-Li, Taiwan*
¹¹⁷*National Taiwan University (NTU), Taipei, Taiwan*
¹¹⁸*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
¹¹⁹*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
¹²⁰*Middle East Technical University, Physics Department, Ankara, Turkey*
¹²¹*Bogazici University, Istanbul, Turkey*
¹²²*Istanbul Technical University, Istanbul, Turkey*
¹²³*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*
¹²⁴*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
¹²⁵*University of Bristol, Bristol, United Kingdom*
¹²⁶*Rutherford Appleton Laboratory, Didcot, United Kingdom*
¹²⁷*Imperial College, London, United Kingdom*
¹²⁸*Brunel University, Uxbridge, United Kingdom*
¹²⁹*Baylor University, Waco, Texas, USA*
¹³⁰*Catholic University of America, Washington DC, USA*
¹³¹*The University of Alabama, Tuscaloosa, Alabama, USA*
¹³²*Boston University, Boston, Massachusetts, USA*

- ¹³³*Brown University, Providence, Rhode Island, USA*
¹³⁴*University of California, Davis, Davis, USA*
¹³⁵*University of California, Los Angeles, California, USA*
¹³⁶*University of California, Riverside, Riverside, USA*
¹³⁷*University of California, San Diego, La Jolla, USA*
¹³⁸*University of California, Santa Barbara—Department of Physics, Santa Barbara, USA*
¹³⁹*California Institute of Technology, Pasadena, California, USA*
¹⁴⁰*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
¹⁴¹*University of Colorado Boulder, Boulder, Colorado, USA*
¹⁴²*Cornell University, Ithaca, New York, USA*
¹⁴³*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
¹⁴⁴*University of Florida, Gainesville, Florida, USA*
¹⁴⁵*Florida International University, Miami, Florida, USA*
¹⁴⁶*Florida State University, Tallahassee, Florida, USA*
¹⁴⁷*Florida Institute of Technology, Melbourne, Florida, USA*
¹⁴⁸*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
¹⁴⁹*The University of Iowa, Iowa City, Iowa, USA*
¹⁵⁰*Johns Hopkins University, Baltimore, Maryland, USA*
¹⁵¹*The University of Kansas, Lawrence, Kansas, USA*
¹⁵²*Kansas State University, Manhattan, Kansas, USA*
¹⁵³*Lawrence Livermore National Laboratory, Livermore, California, USA*
¹⁵⁴*University of Maryland, College Park, Maryland, USA*
¹⁵⁵*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
¹⁵⁶*University of Minnesota, Minneapolis, Minnesota, USA*
¹⁵⁷*University of Mississippi, Oxford, Mississippi, USA*
¹⁵⁸*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
¹⁵⁹*State University of New York at Buffalo, Buffalo, New York, USA*
¹⁶⁰*Northeastern University, Boston, Massachusetts, USA*
¹⁶¹*Northwestern University, Evanston, Illinois, USA*
¹⁶²*University of Notre Dame, Notre Dame, Indiana, USA*
¹⁶³*The Ohio State University, Columbus, Ohio, USA*
¹⁶⁴*Princeton University, Princeton, New Jersey, USA*
¹⁶⁵*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
¹⁶⁶*Purdue University, West Lafayette, Indiana, USA*
¹⁶⁷*Purdue University Northwest, Hammond, Indiana, USA*
¹⁶⁸*Rice University, Houston, Texas, USA*
¹⁶⁹*University of Rochester, Rochester, New York, USA*
¹⁷⁰*The Rockefeller University, New York, New York, USA*
¹⁷¹*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
¹⁷²*University of Tennessee, Knoxville, Tennessee, USA*
¹⁷³*Texas A&M University, College Station, Texas, USA*
¹⁷⁴*Texas Tech University, Lubbock, Texas, USA*
¹⁷⁵*Vanderbilt University, Nashville, Tennessee, USA*
¹⁷⁶*University of Virginia, Charlottesville, Virginia, USA*
¹⁷⁷*Wayne State University, Detroit, Michigan, USA*
¹⁷⁸*University of Wisconsin—Madison, Madison, Wisconsin, USA*

^aDeceased.

^bAlso at Vienna University of Technology, Vienna, Austria.

^cAlso at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

^dAlso at Universidade Estadual de Campinas, Campinas, Brazil.

^eAlso at Universidade Federal de Pelotas, Pelotas, Brazil.

^fAlso at Université Libre de Bruxelles, Bruxelles, Belgium.

^gAlso at Joint Institute for Nuclear Research, Dubna, Russia.

^hAlso at Suez University, Suez, Egypt.

ⁱAlso at British University in Egypt, Cairo, Egypt.

^jAlso at Helwan University, Cairo, Egypt.

^kAlso at Université de Haute Alsace, Mulhouse, France.

^lAlso at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

^mAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

- ⁿ Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
- ^o Also at University of Hamburg, Hamburg, Germany.
- ^p Also at Brandenburg University of Technology, Cottbus, Germany.
- ^q Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ^r Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
- ^s Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
- ^t Also at IIT Bhubaneswar, Bhubaneswar, India.
- ^u Also at Institute of Physics, Bhubaneswar, India.
- ^v Also at University of Visva-Bharati, Santiniketan, India.
- ^w Also at University of Ruhuna, Matara, Sri Lanka.
- ^x Also at Isfahan University of Technology, Isfahan, Iran.
- ^y Also at Yazd University, Yazd, Iran.
- ^z Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- ^{aa} Also at Università degli Studi di Siena, Siena, Italy.
- ^{bb} Also at INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy.
- ^{cc} Also at Purdue University, West Lafayette, USA.
- ^{dd} Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- ^{ee} Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- ^{ff} Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
- ^{gg} Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ^{hh} Also at Institute for Nuclear Research, Moscow, Russia.
- ⁱⁱ Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ^{jj} Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ^{kk} Also at University of Florida, Gainesville, USA.
- ^{ll} Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ^{mm} Also at California Institute of Technology, Pasadena, USA.
- ⁿⁿ Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ^{oo} Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ^{pp} Also at INFN Sezione di Roma, Sapienza Università di Roma, Rome, Italy.
- ^{qq} Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ^{rr} Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ^{ss} Also at National and Kapodistrian University of Athens, Athens, Greece.
- ^{tt} Also at Riga Technical University, Riga, Latvia.
- ^{uu} Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ^{vv} Also at Stefan Meyer Institute for Subatomic Physics.
- ^{ww} Also at Istanbul University, Faculty of Science, Istanbul, Turkey.
- ^{xx} Also at Istanbul Aydin University, Istanbul, Turkey.
- ^{yy} Also at Mersin University, Mersin, Turkey.
- ^{zz} Also at Cag University, Mersin, Turkey.
- ^{aaa} Also at Piri Reis University, Istanbul, Turkey.
- ^{bbb} Also at Gaziosmanpasa University, Tokat, Turkey.
- ^{ccc} Also at Adiyaman University, Adiyaman, Turkey.
- ^{ddd} Also at Izmir Institute of Technology, Izmir, Turkey.
- ^{eee} Also at Necmettin Erbakan University, Konya, Turkey.
- ^{fff} Also at Marmara University, Istanbul, Turkey.
- ^{ggg} Also at Kafkas University, Kars, Turkey.
- ^{hhh} Also at Istanbul Bilgi University, Istanbul, Turkey.
- ⁱⁱⁱ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ^{jjj} Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{kkk} Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- ^{lll} Also at Utah Valley University, Orem, USA.
- ^{mmm} Also at Beykent University.
- ⁿⁿⁿ Also at Bingol University, Bingol, Turkey.
- ^{ooo} Also at Erzincan University, Erzincan, Turkey.
- ^{ppp} Also at Sinop University, Sinop, Turkey.
- ^{qqq} Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ^{rrr} Also at Texas A&M University at Qatar, Doha, Qatar.
- ^{sss} Also at Kyungpook National University, Daegu, Korea.